Floating Capacitor Active Charge Balancing for PHEV Applications

A Thesis

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By

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ABSTRACT

Li-ion battery chemistry provides high energy density, which is extremely important for plug-in hybrid vehicles (PHEV). However, Li-ion batteries are also more prone to damage by overcharging and over-discharging. For PHEV applications, a battery pack consists of many battery cells in series and parallel configurations. Over time, the state of charge (SOC) of individual cells can deviate from one another because of various conditions and manufacturing variability, increasing the likelihood of overcharging and/or over-discharging individual cells. This project explores the use of a floating capacitor active charge balancing (ACB) system for a Li-ion battery pack. A prototype floating capacitor ACB system is built and implemented in a custom built pack consisting three parallel strings with four cells in each string (3P4S). The battery pack is exercised on a cycler to deviate the SOCs of the cells, and the ACB system is used for no-load balancing. Results verify previous simulations of the same system. The floating capacitor ACB system sufficiently balances the pack with no load balancing. In addition, the system is made of simple components, decreasing complexity and provides good economic efficiency.

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CHAPTER 1

Introduction

1.1 Motivation

For plug-in hybrid electric vehicles (PHEV) and electric vehicles (EV), the battery pack is vitally important for the performance of the vehicle. Lithium-ion (Li-Ion) battery chemistry provides higher energy density than other battery chemistries such as Nickel-Metal Hydride (NiMH). However, Li-ion batteries are more prone to damage by overcharging and over-discharging. Adding to the complexity, batteries are connected in both series and parallel for PHEV and HEV application to provide the needed power and capacity.

Over periods of use, individual cell voltages in a battery pack deviate from one another because of slight manufacturing differences. The deviation of voltages may result in possible overcharging or over-discharging of certain cells, decreasing the state of health (SOH) of the battery pack. Thus, a cell balancing circuit is needed, keeping the state of charge (SOC) of each battery close to one another.

Many charge balancing techniques have been proposed. There are two main categories for charge balancing methods. Passive charge balancing (PCB) consists of dissipating energy from batteries with higher voltage, bringing their SOC's down close to the batteries with the lower SOC's. Active charge balancing (ACB) consists of transferring energy from higher charged batteries to lower charged ones, bring them to similar SOC's.

An active charge balancing system was proposed, consisting of a floating capacitor system. The system is designed to balance a 12V battery pack with three parallel strings, each string consisting of four cells in series (3P4S). The balancing circuit uses only one capacitor for the entire pack. The capacitor is designed to float and connect to any battery in the pack, across the parallel strings and through the series. It is used to shuttle charge between higher and lower charged batteries. The balancing is assumed to be done during no load conditions.

A charge equalization circuit was designed and implemented using the floating capacitor method. The circuit was designed to support and verify simulations ran by Jim Welsh [1] [2].

1.2 Cell Balancing Literature Review

Even before the advances in Li-ion battery chemistry, charge balancing is determined to be important in maintain cell SOH in a battery pack for EV purposes. Although NiMH batteries cells have natural gassing to releases excess energy in overcharging situations, charge balancing is still important to keep its SOH at a high level. A charge equalization technique is proposed for NiMH battery packs for EV applications [3]. The proposed scheme consists of a bulk charging system and a charge equalization system. The charge equalization system uses an isolated dc-to-dc converter with a multiwinding transformer. The system directs charge from a source to the weakest cell in the pack. Once the weakest cell reaches the same charge as the second weakest cell, the system directs charge to both. This process repeats until the entire battery pack is fully charged.

Charge balancing for Li-ion battery packs is more important since it is more prone to damage from overcharging and over-discharging. Several charge equalization techniques have been proposed. The three main categories of balancing methods are charging, active, and passive [4].

End of charge methods are useful for EV purposes since they are usually fully charged between use cycles. One end of charge technique is charge shunting. Once a cell in a battery pack is fully charged, the charging current is shunted away from that particular cell. This ensures no cells overcharge and are all fully charged at the end of the charge cycle.

There are several active charge balancing techniques. A capacitor circuit can be used to shuttle charge between the cells, similar to the technique explored in this thesis. Charge shuttling removes excess energy from the higher charged cells and moves it to the weaker charged cells. Several capacitor circuits can be put into cascade for battery packs with higher number of cells. Charge shuttling provides the advantage of simplicity at the cost of lower balancing efficiency. Another active balancing technique used is with energy converters. Energy converters use inductors or transformer to transfer energy between the cells. Energy converters provide the advantage of fast balancing rate at the cost of complexity and energy loss switching losses and magnetic losses.

Passive balancing techniques include the use of dissipative resistors. Dissipative resistors remove excess energy from the higher charged cells in the pack to bring all cells to the same SOC. They provide low complexity but have high energy losses.

Although the charge shuttling technique has low balancing efficiency, it can be improved by the use of a two tier system [5]. In a single tier system, charge is directly exchanged within adjacent cells. It takes time for cells that are further away in the pack to exchange charge since it needs to go through several capacitors. By adding a second tier of capacitors in parallel, the balancing rate is increased by allowing charge exchange between non-adjacent cells.

All proposed charge balancing techniques have advantages and disadvantages. However, all the presented techniques explore charge balancing for series connected batteries. They do not explore charge balancing across parallel connections. As stated, parallel connections are important for a battery pack for PHEV and EV applications to increase the energy capacity. The proposed floating capacitor ACB system is explored for its balancing efficiency in series and parallel connections.

1.3 Outline of Thesis

The thesis is presented in the following chapters. Chapter 2 covers the circuit implementations for a circuit with 2 battery cells in series and also the 3P4S battery pack. It focuses on the circuit hardware design the ACB system. Chapter 3 describes the control algorithm and covers the experimental results. Chapter 4 provides discussions of the experimental results. Lastly, chapter 5 provides a summary of the research and suggestions for future work based off of this research.

CHAPTER 2

ACB Harware Implementation

This chapter covers the harware implementation of the floating capacitor ACB system. The first section will cover ACB implementation for two batteries connected in series. The second section will cover ACB implementation for the custom table top 12V battery pack.

2.1 Two Cell ACB Circuit

Before the floating capacitor ACB circuit was designed and implemented for the table top battery pack, hardware was first designed for two batteries connected in series (2S) to reduce complexities. The design for the two cell circuit would then be the basis for the 12V battery pack. The circuit for the two batteries in series is simple, which is shown in Figure 2.1. It consisted of two batteries in series with the positive and negative terminals of each one connected to the capacitor. Each connection is closed and opened by a switch. This allows either battery to be connected to the capacitor at a given time and shuttles charge between the two cells when switched back and forth.

The batteries used are A123 Li-ion cells with nominal voltage of 3.3V and nominal capacity of 2.3Ah. The initial capacitor used is a Maxwell BMOD0058 15V 58F

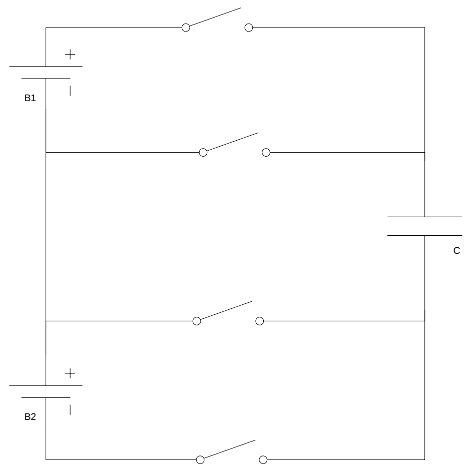


Figure 2.1: Two Cell Circuit

Ultracapacitor. Most of the circuit design involves the switching choice. For preliminary testing, a manual DPDT switch is used. The purpose of the manual switch is to verify charge shuttling between the two cells. For preliminary testing with automated controls, a two pole miniature power PC board relay was used. The relay offers simple implementation at low frequency switching.

From simulations, it is determined that for efficient charge shuttling, circuit series resistance must be reduced as much as possible. Also, it is determined charge shutting is more efficient at a higher switching frequency. Thus, solid state components should be used for the final switching design. Solid state components provide higher switching frequency and, unlike relays, do not contain moving parts, increasing its reliability. The switch must be bi-directional since it cannot be determined before implementation whether a cell would need to be charged or discharge, and it must fit the requirement of very low on resistance. CMX60D10 solid state relays (SSR) are used, which have on resistance of 0.018Ω. The SSR works well in implementation. However, they are also expensive, reducing the cost effectiveness drastically when used for a battery pack with multiple cells. Si6968BEDQ dual N-channel common drain MOSFET fits all design requirements. It has low on resistance of 0.022Ω, and being common drain, it is able to block current in both directions during off mode.

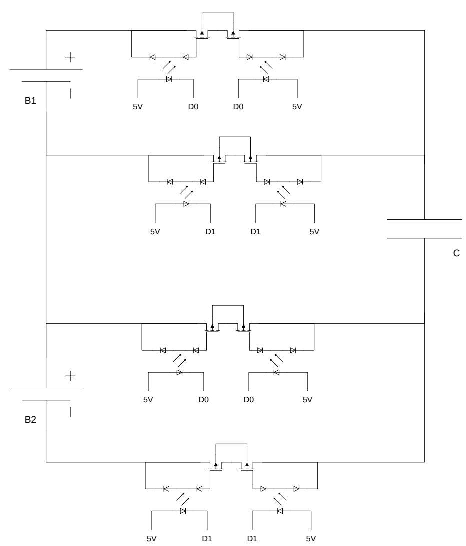


Figure 2.2: Two Cell Final Circuit

However, difficulties arose for biasing. Because of the circuit set up, it was possible for voltage from a battery to turn on a MOSFET unintentionally when using unisolated biasing methods. This was a big problem because of the possibility of shorting the circuit components from the biasing or control signals, causing potential damage to the components in the circuit. This problem was solved using PVI5080NPbF photo voltaic isolators (PVI). The PVI's isolated the control signal and the biasing voltage for each MOSFET, preventing the voltages from the batteries from unintentionally turning on other MOSFET's. A PVI was used for each MOSFET (two per switch), opening and closing a switching for bi-directional current. The final circuit design for the 2 cell in series ACB circuit is shown in Figure 2.2. For this circuit, the user may choose different capacitors or extra series resistors.

2.2 12V Battery Pack ACB Circuit

The final ACB circuit for the 12V custom table top battery pack is an expansion of the circuit for the two cell in series. The circuit is expanded for four cells in series, and three of those circuits are made for the 3 parallel strings. The final circuit design is shown in Figure 2.3. Only the 58F capacitor is used for this circuit. No extra series resistance is added, resulting in total series resistance of 0.052Ω.

As with the two cell circuit design, two PVI's are used for one switch, allowing for only one single cell to be connect to the capacitor when determined by the control algorithm. The circuits are made using printed circuit boards, which can be seen in Figure A.1. Figure A.2 shows the schematic for the board.

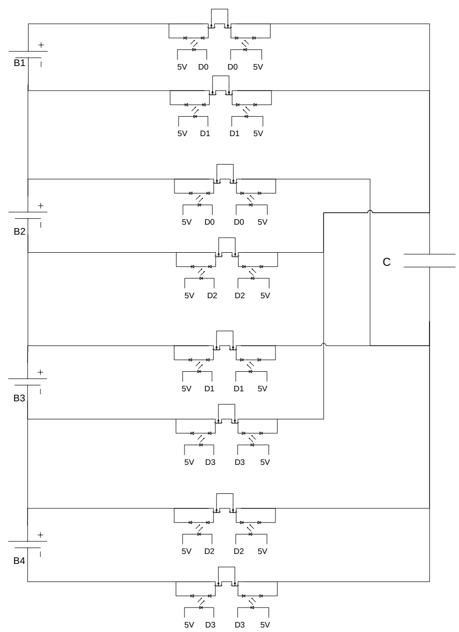


Figure 2.3: 12V Custom Table Top Pack Final Circuit

CHAPTER 3

Experimental Results

This chapter covers the results of the various circuit implementations. The first section covers test results for 2S circuit, including results from manual switching, relay automated switching, and SSR switching. The second section covers test results for the custom table top 12V battery pack. Both sections also describe the controla algorithm used for experimental testing.

3.1 2 Cell ACB Circuit

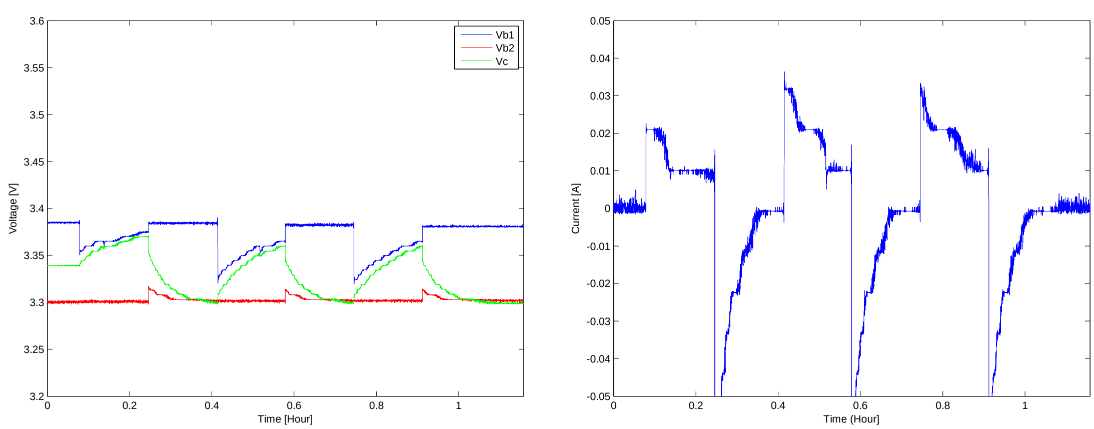
3.1.1 Control Algorithm

Since there are only two battery for charge shuttling in the 2S cell in series circuit, the control algorithm is not required to determine which battery should be connected to the capacitor. The two cells simply need to be switched back and forth to the capacitor with the two batteries set at different SOC's. The control algorithm is written as MATLAB m files. NI USB6008 DAQ is used for data acquisition and control signal source.

To start balancing, the user chooses the balancing time period, series resistance value, capacitance value, and time constant factor. The algorithm calculates the circuit time constant based on the resistance and capacitance value, and the switching time period based on the time constant and the time constant factor. The two cells are then switched back and forth to the capacitor, but two switching time periods are left before and after the switching to record the start and end voltage values. Voltages of both cells and the capacitor are recorded with NI USB6008 DAQ. The voltages are plotted in real time during the test, allowing the user to monitor the balancing progress and also any possible problems. The plot is updated at 1Hz.

3.1.2 Results

The digitally filtered recorded data for the manual switching circuit is shown in Figure 3.1(a) and Figure 3.1(b). Figure 3.1(a) shows the battery voltages and the capacitor voltage. Figure 3.1(b) shows the circuit current calculated from the recorded resistor voltage. Table 3.1 shows measurements taken at the start and end of the test. The SOC difference between the two batteries decreased by about 0.0470%.



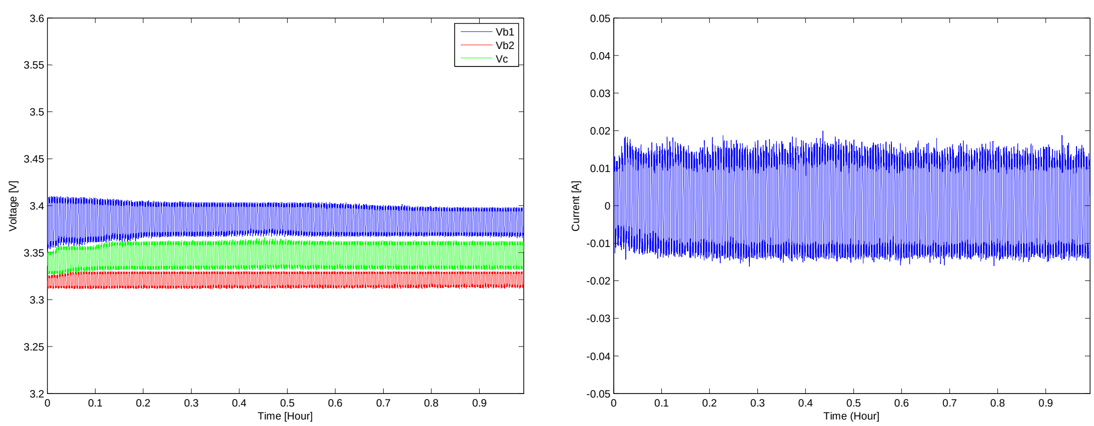
(a) Voltage

(b) Induced Current

Figure 3.1: Manual Switching Circuit Results

Table 3.1: Manual Switch Run		
	Start	End
Vb1	3.381	3.379
Vb2	3.298	3.299
Vc	3.339	3.299
Delta SOC	2.1279%	2.0529%

For the relay circuit, three 1 hour tests are run consecutively after one another. Figures 3.2(a) & 3.2(b) and Table 3.2 show data collected from the second run. The SOC difference decreased by an average of 0.1345% in the three test runs with standard deviation of 0.0521%.



(a) Voltage

(b) Induced Current

Figure 3.2: Relay Automated Switching Circuit Results

Table 3.2: Relay Test 2

	Start	End
Vb1	3.401	3.392
Vb2	3.312	3.313
Vc	3.338	3.345
Delta SOC	1.8043%	1.6606%

For SSR circuit tests, Figure 3.3 shows the digitally filtered data of the test that was run with 0.250 Ω resistance and 58 F capacitance. The dynamics of the each signal behaved as expected. The rate of charge shuttling decreases exponentially as time went on, and the capacitance voltage also settles to between the battery voltages. All tests show similar dynamics. Table 3.3 shows the first and second tests of each combination of resistance and capacitance. The data shows the change in SOC difference between the start and end of the tests.

Table 3.3: SSR Various Components

	58 F		150 F	
	First	Second	First	Second
0.250 Ω	11.0819%	10.8474%	5.1875%	2.1263%
0.450 Ω	1.3290%	1.3046%	2.1034%	2.1131%
12.450 Ω	0.5301%	0.5331%	0.1089%	0.0018%

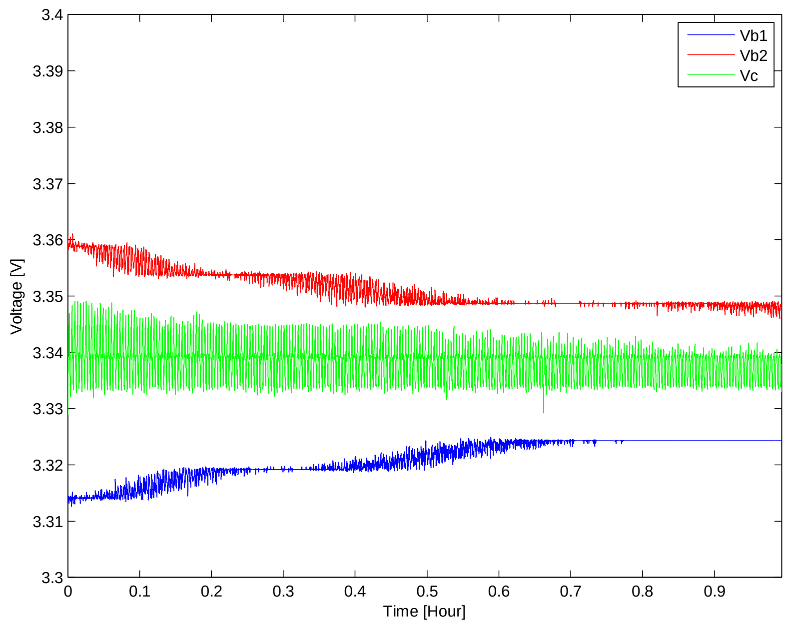


Figure 3.3: SSR Switching Circuit Results

3.2 12V Battery Pack ACB Circuit

3.2.1 Control Algorithm

The control algorithm for balancing the 12V battery pack follows a rule based appraoch [1]. Unlike the control for the 2S circuit, the control algorithm for the 12V battery pack does need to determine which cell was to connect to the capacitor at a given time. Using similar methods as the simulations, the controller determines the two cells with maximum and minimum SOC's in the pack. This takes advantage of the maximum voltage difference between two cells in the pack, resulting in largest charge shuttling current.

For the 12V battery pack balancing algorithm, the user chooses the balancing time period and the time constant factor. Since only the 58F capacitor is used without extra series resistance, the time constant remains the same for all balancing runs. The switching time period is controlled by the user only by the time constant factor. Cell voltages are sampled at 2000Hz by the DAQ. Cell voltages for the controller are updated at 1Hz. The sample from the DAQ are processed using a moving average filter. Every second, the controller took the last 1000 samples from the DAQ for each cell voltage and calculates the average of the samples. This prcoess reduces random noise from the DAQ or the battery pack. At the switching frequency, the capacitor is switched back and forth between the maximally and minimally charged cells. During each switching period, the controller checks for the maximally and minimally charged cells from the last filtered samples acquired from the DAQ.

Unlike the 2 cell circuit, the voltages of the 12V battery pack are not plotted in real time during balancing. All control and processing are done using MATLAB. Since there are 12 difference voltages as compared to 3 different voltages to plot, updating the figure in real time slows down MATLAB and reduces the switching frequency because of the extra processing needed to update the figure. Since there is no real time plot of the cell voltages, the ability to monitor balancing status is reduced. It is possible, however, to monitor the maximum and minimum cell voltages through the MATLAB workspace. Constant monitoring of those two values give indication of the status of balancing and possible errors in the system.

3.2.2 Results

The data collected for the 3P4S pack are processed and denoised using the wavelet toolbox in MATLAB. The experiment tests were four hours long with 0.1 time constant factor. The denoised data can be seen in Figure 3.4. Table 3.4 shows the maximum and minimum cell voltages at the start and end of the test. It also shows the calculated largest SOC difference between 2 cells in the pack based off the maximum and minimum cell voltages. The SOC difference decreased by 5.4562% in the 4 hour test period.

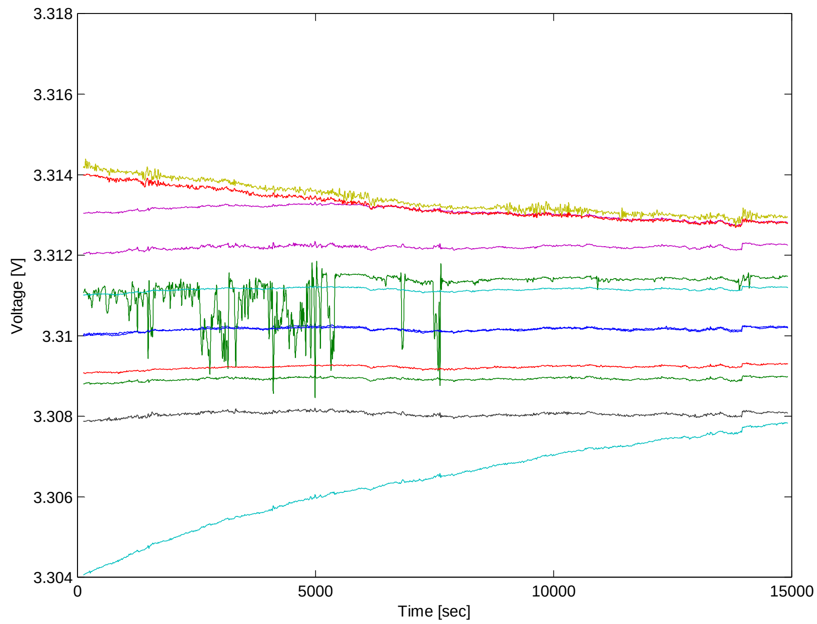


Figure 3.4: 12V Table Top Pack Balancing Results

Table 3.4: 12V Battery Pack Test Data

	Start	End
Vmax	3.3147	3.3128
Vmin	3.3038	3.3079
Delta SOC	9.8941%	4.4379%

CHAPTER 4

Discussion

This chapter discusses the results of the various circuit implementations. The first section discusses test results for the 2S circuit, including results from manual switching, relay automated switching, and SSR switching. The second section discusses test results for the custom table top 12V battery pack.

4.1 2 Cell ACB Circuit

The test run for the manual switching circuit verifies the simulations [2]. As can be seen in Figure 3.1(a), there is a battery voltage drop or rise when the balancing capacitive circuit was connect to battery 1 or battery 2, respectively. This results from the internal resistance of the batteries. Figure 3.1(a) shows the expected behavior of the capacitive balancing circuit. When the capacitor is connected to a battery at a higher voltage, the battery charges the capacitor. When the capacitor is connected to a battery at a lower voltage, the capacitor charges the battery. Although there was only very slight voltage change from the start to the end of the run, charge shuttling was still confirmed. The data shown in Table 3.1 verifies that there was charge shuttled between the two batteries, as battery 1 voltage decreased and battery 2 voltage increased.

The results from the automated circuit verify the simulations [2]. From simulations results based on the circuit resistance, the SOC difference should decrease between 1.073% to 0.1399% for a 1 hour test with switching period at 1 time constant. From the three test runs, the SOC difference decreased an average of 0.1345%. The average decrease comes close to being within the range determined from the simulations. There are several factors that may have affected the results to be slightly out of range. First, the SOC estimations from the voltage measurements may not be accurate. The voltage measurements taken are to the order of 1 mV. However, voltage variations of 900 μV may affect the SOC difference calculation by about 0.03% around the voltage range of the experimental tests. As shown in results from test 3, the voltage measurements of battery 2 indicates that it was not charged as expected. However, the induced current result from test 3, which is similar to Figure 3.2(b), shows that there was charging done on battery 2 since there was consistent negative current through the power MOSFET during the test, indicating discharge from the capacitor to a battery. Thus, the slight inaccuracy of the voltage measurement may have resulted in inaccuracies in SOC difference calculation.

Another factor may be the SOH of the batteries. During a test run, the medium capacitor voltage is expected to reach a steady-state in between the higher and lower battery voltages. Experimental tests 2 and 3 confirm this expectation. However, the first experimental test shows inconsistency in the expected behavior. The capacitor voltage does not reach steady state. Instead, it rises and drops in a seemingly random pattern. Also, the charge and discharge currents also exhibit a random pattern. A battery with low SOH has inconsistent charge and discharge rates. From the data, it may be inferred that battery 1 may be reaching the end of its life. Because of inconsistent charge and discharge rates, the balancing circuit does not shuttle the charge with expected efficiency, resulting in lower SOC difference decrease than expected.

The results from the relay balancing circuit verify the expectation of charge shuttling. SOC difference between the two batteries decreased during each test. Overall, the three consecutive experimental tests decrease the SOC difference by 0.3266% in three hours. The SOC difference decrease also decreased as expected. As the voltage difference between the two batteries became smaller, the voltage difference between the batteries and the capacitor also became smaller, decreasing the charging and discharging current. This resulted in decrease in rate of charge shuttling. Also, from the test runs and simulation results, it may be inferred that the circuit resistance is close to 1 Ω, indicating a higher resistance than the calculated resistance from the rated resistances of the components.

SOC estimation for the manual and relay automated switching circuits are done using the manufacturer give SOC curve. For the SSR switching circuit an in house tested SOC curve, which can be seen in 4.1, is used for SOC estimation instead to obtain more accurate data. The SSR switching circuit charge shuttling tests are run in the 70% to 95% test to utilize the elbow region of the SOC curve, as can be seen in Figure 4.1, for more accurate SOC estimations. Realistically, the SOC difference should not be that drastic. It is only set so for testing purposes. The relationship between rate of charge shuttling and different resistance and capacitance can be seen in Table 3.3. As expected, the rate of SOC difference decreases as the series resistance increases. This is consistent with previous experiments. As the resistance increases, the charging and discharging current decreases, resulting in slower charge shuttling.

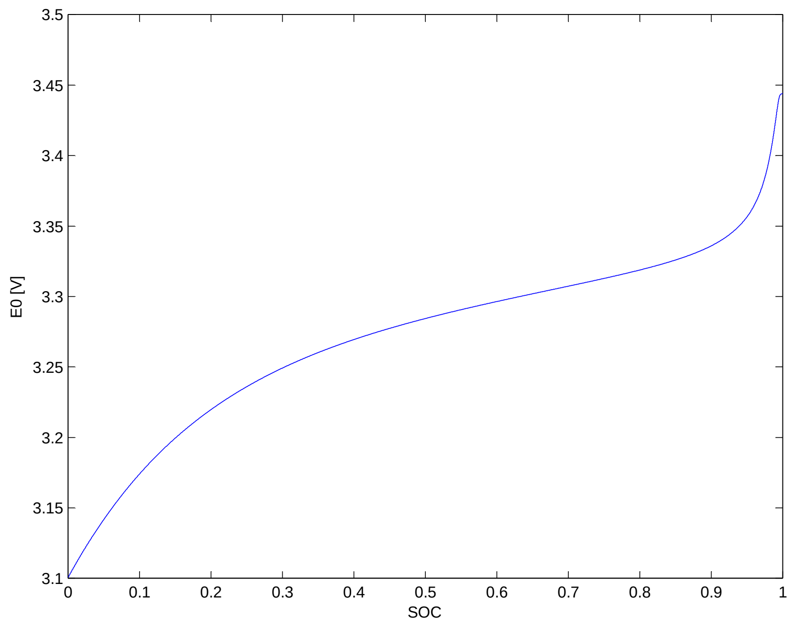


Figure 4.1: Experimental Tested SOC Curve

The relationship between capacitance and the charge shuttling rate is less conclusive. At 0.250 Ω and 12.250, 150 F has slower charge shuttling rate than 58 F, However, at 0.450 Ω, 150 F has a faster charge shuttling rate than 58 F.

Also, it is shown that the SOC difference is consistent when using 58F, as the first and second tests for both resistance values have around the same SOC difference. However, 150 F is shown to be inconsistent except for 0.450 Ω. The first and second tests for the other two resistance values have much different charge shuttling rate. This may have been caused by the implementation of the capacitor. The 150 F capacitance is realized by connecting two 300F capacitors in series, since both are rated at 2.7 V. They need to be connected in series to reach the desired voltage around 3.3 V. The slight manufacturing difference in each of the capacitors may have caused the inconsistency of the results. The inconsistency is shown in the difference in the voltage of each capacitor. Even though the overall capacitor voltage is at the desired values, the two capacitors show difference in voltage despite setting them equal at the start of testing.

4.2 12V Battery Pack ACB Circuit

The 4 hour experimental test for the 12V table top battery pack shows the designed floating capacitor circuit is able to efficiently reduce the SOC difference in the battery pack. In 4 hours of no load balancing, the ACB circuit is able to reduce the the maximum SOC difference between 2 cells in the pack by 5.4562%. Figure 3.4 shows the ACB system behaved as expected. Charge is shuttled between the maximumally and minimally charged cells in the pack, which in this test are cell 6 and cell 11, respectively.

As the voltage of cell 6 is discharged down to the voltage of the second most charged cell, cell 10, both cell 6 and cell 10 become involved in the charge shuttling process. This is the difference between charge balancing for the 2S battery pack and the 3P4S battery pack. For the 2S pack, charge is only shuttled between the two cells. The control algorithm does not need to make a decision of which cell to connect to the capacitor. For the 12V pack, the control algorithm does need to make that decision. As can be seen, when cell 6 and cell 10 are the maximally charged cells in the battery pack, one cell is discharged until it is lower than the other, then the other cell is discharged in the charge shuttling process. This shows correct operation of the control algorithm. Also, since there are two cells involved in discharging, while only one cell is involved in charging, the discharge rate is slower than the charge rate.

The floating capacitor is shown to be able to balancing charge efficiently in series and also across parallel connections in a battery pack. All three cells involved in charge shuttling in this test are in different strings. The experimental test also presents a realistic situation. Prior to the balancing test, the battery pack was used in several charge and discharge runs using a charge cycler. The battery pack was then laid to rest for a long period. The SOC imbalance seen in the battery pack at the start of balancing was caused by normal operation and natural discharge of the battery pack. In mere 4 hours of balancing time, the floating capacitor ACB circuit is able to reduce the maximum SOC difference in the pack by more than half.

CHAPTER 5

Conclusion

5.1 Summary

Both the manual and automated balancing circuits verify the simulations in the capacitive circuit's ability to shuttle charge between two batteries with difference SOC. More accurate results may be recorded with batteries that have better SOH and a DAQ with better voltage resolution.

Results indicate that the relay circuit resistance is around 1 Ω. From simulations, the expected SOC difference decrease is about 0.14% for a 58 F capacitor in one hour. This rate of charge shuttling is not efficient enough to prevent overcharging or over-discharging during operation. Thus, it is important to implement a circuit with lower circuit resistance. Low resistance results in higher charge and discharge current, resulting in faster charge and discharge rates.

Even with the use of an in house SOC curve, the experimental tests prove the floating capacitor method to efficiently shuttle charge between two batteries. At 0.250 Ω, 58F, and 0.5 time constant factor switching rate, the SOC difference decreases about 10.9% in one hour. In a no load condition, that should be efficient enough balancing the charges given several hours for balancing. It should be noted that 70% to 95% is a big SOC range, and cells in a battery pack should realistically not reach such drastic differences. The range is used to provide more accurate results in voltage reading because of the elbow region of the SOC curve.

The experimental balancing test with the 3P4S battery pack shows that the floating capacitor ACB circuit is able to effectively balance cell charges in series and across parallel connections. Maximum SOC difference was reduced by more than half for a pack that was in a realistically unbalanced state. The designed switching technique and circuit provides a basis for parallel battery pack balancing using a floating capacitor ACB system.

5.2 Future Work

Additional experimental data should be gathered for the 12V custom table top battery pack. Experiments should be run on various ranges of the SOC curve to explore the effectiveness of the floating capacitor ACB across the entire SOC range. Experiments simulating realistic situations, such as balancing the battery pack after running it in a realistic current profile, can be done. Additional analysis should be done on the acquired data. It is important to determine the energy efficiency of the floating capacitor ACB system. Additional voltage or current measurements should be taken to acquire the required data to calculate energy loss during balancing. A PCB system can also be designed and implemented based off of simulations. The experimental data collected for the PCB system can then be compared with the data from the ACB system.

More advanced switching and circuit design can be implemented. With the circuit design proposed in this thesis, the circuit series resistance was able to be reduced to as low as 0.052Ω using the Si6968BEDQ dual N-channel common drain MOSFET's.

With a more advanced design, the series resistance may be reduced even more, which would result in higher charge shuttling currents and higher charge balancing efficiency.

More advanced controller can be implemented. The controls for all experiments were done using MATLAB. As stated before, monitoring cell voltages using MATLAB plots for the 3P4S battery pack experiments was eliminated due to insufficient computing power. More advanced programs, such as LabVIEW, may be used to provide constant monitoring without affecting timing of the control algorithm. This is important to prevent anomalies and malfunctions during balancing tests. In addition, more advanced SOC estimation methods should be implemented. All SOC calculations presented in this thesis are done using a predetermined SOC curve. It cannot be directly calculated. Instead, it is calculated based on the measured voltage of the battery cells. This method only provides a crude estimation of SOC as it does not consider factors such as the SOH of the cells. A more advanced SOC estimatino technique would provide more accurate results and better operation of the ACB system.

APPENDIX A

Floating Capacitor ACB System Manual

A.1 Hardware

Figure A.1 shows the layout of the printed circuit board for the 3P4S battery pack. A single circuit board is for a single four cell string in the battery pack. Figure A.2 shows the corresponding schematic for the circuit board. The top left 6-pin terminal on the board is for the control signals from the DAQ. The first pin connects to the 5V source from the DAQ. The third, fourth, fifth, and sixth pin connects to the first, second, third, and fourth digital output signal from the DAQ for the string. The bottom left 8-pin terminal on the board is for the four cells in the string. Following in the schematic in Figure A.2, only 5 pins need to be connected. The top right 2-pin terminal is for the capacitor.

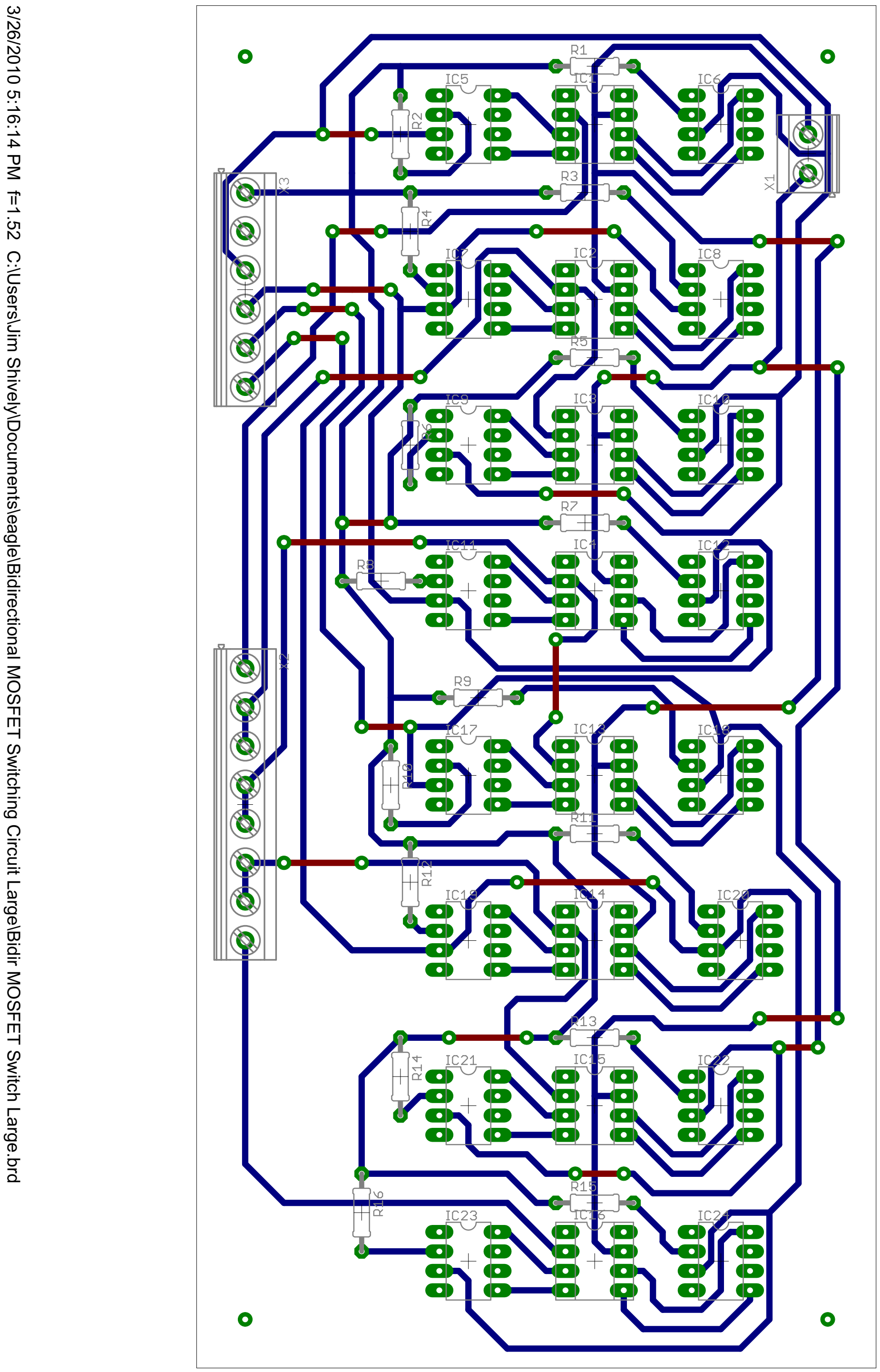


Figure A.1: ACB Circuit Board

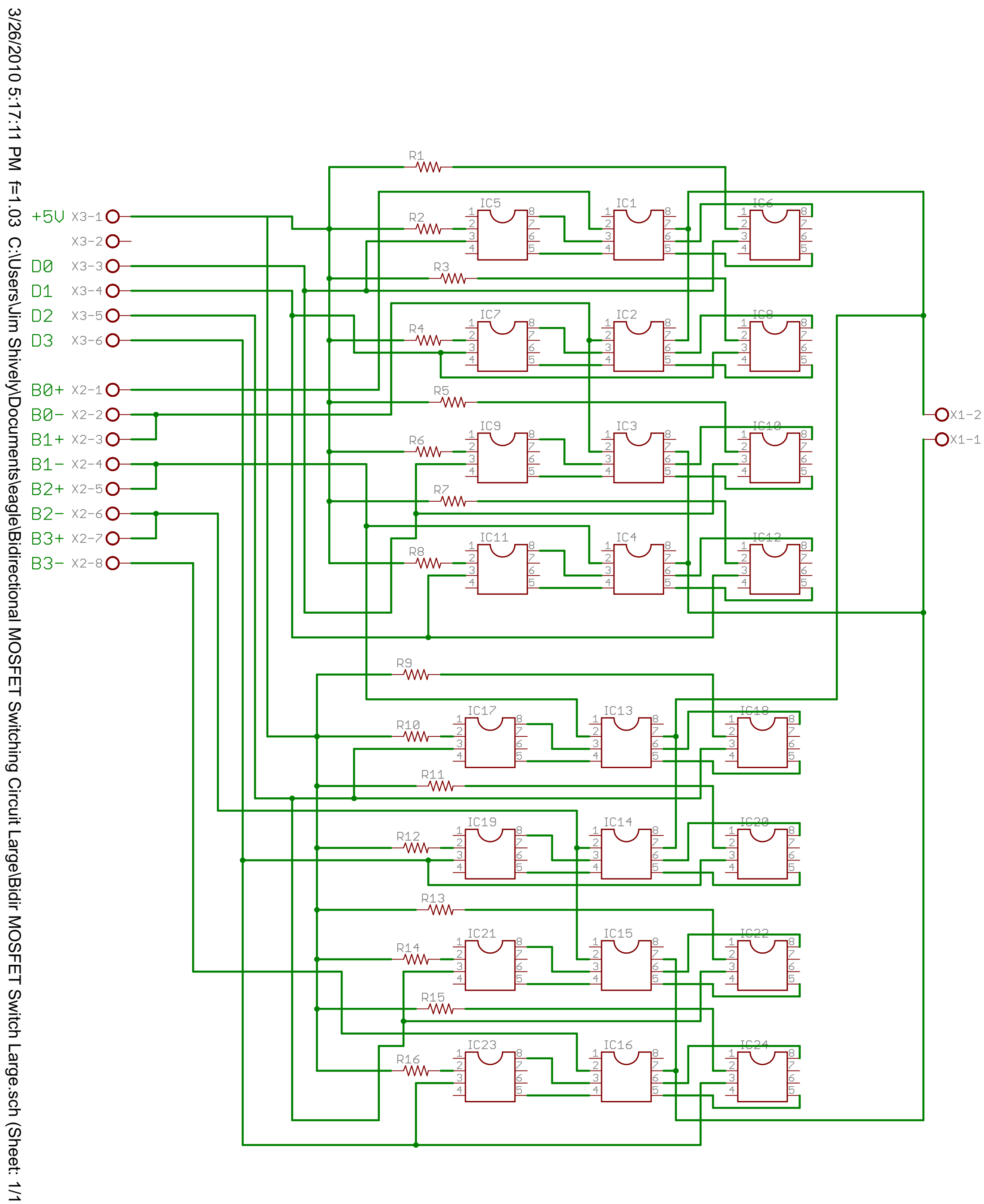


Figure A.2: ACB Schematic

A.2 Instructions

Follow these instructions for 3P4S pack balancing.

1. Start MATLAB and run start.m. This will initiate and analog inputs and digital output of the NI PCI 6259 DAQ.

2. Connect power source of battery pack to outlet.

3. Connect cable from PCI 6259 DAQ to connector block on battery pack. (NOTE: It is extremely important to run start.m before connecting the DAQ to the cable block. This is because the designed circuit utilizes the 5V source on the DAQ. Before start.m is run, the 5V source to all digital outputs are at 5V. Running start.m initializes the digital outputs to 5V, making 5V to all digital outputs at 0V. Failure to run start.m before connection will close all switches and short all cells and may cause significant damage to the circuit and and/or battery pack.)

4. Select "Run Shuttle Test" shortcut.

5. Input balancing time (in hours).

6. Input time constant factor.

7. Control algorithm for battery pack balancing runs. Currently, balancing status can be monitored with the MATLAB workspace. It is advised to monitor the maximum and minimum cell voltages in the pack.

8. Acquired data automatically saves after balancing.

9. If balancing test needs to be stopped at any point, select “Stop Shuttle Test” shortcut. This opens up all switches, reset all balancing variables, and save data that has been acquired.

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